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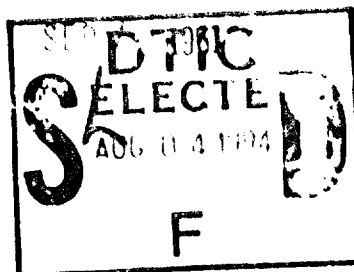
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## Structural Designers' View of Criteria Trends

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Adopting the point of view of the structural designer, available structural criteria are reviewed with respect to the demands for new criteria for a variety of advanced flight vehicle types. The basic needs of the structural designer are delineated in relation to his specific function of crystallizing the configuration arrangement and element cross-section area details of the structural components. The nature of the criteria required in design of several new types of flight vehicles is outlined. It is shown that a considerable amount of basic structural criteria is applicable to almost all flight vehicles. A new arrangement for structural requirement specifications is advocated.

142

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# Structural Designers' View of Criteria Trends

ROBERT GOLDIN

The exploding rate-of-expansion of flight-vehicle performance is imposing rigorous demands upon the structural design criteria engineer. Ever since World War II the variety of aircraft being developed has required whole new categories of structural design criteria. In 1945, when the Bell X-1 airplane was being designed to crack the sonic barrier, our prime concern was, "To what structural criteria should a trans-sonic and supersonic aircraft be designed?" At about the same time helicopter criteria was being crystallized. Following in rapid succession were the demands for missile, VTOL, boost-glide, and satellite criteria. A new type vehicle, the ground effect machine, and space craft, also are demanding establishment of new structural criteria. Since the ultimate user of structural criteria is the airframe designer, the complexity of the problem can be reduced if we determine the designer's general needs before formulating specific answers.

Fundamentally, there are two basic reasons for creation of structural criteria specifications: (a) To provide a mutually satisfactory basis for understanding of strength to be provided between the customer and the contractor, and (b) to provide the presumptions and conditions for use in determination of appropriate structural materials and cross-sectional areas. The first reason is evidenced continually during the life of a flight-vehicle contract as the customer seeks to determine by review of analyses and tests if the completed vehicle will perform as desired. The second reason is evidenced in the contractor's organization by the constant questioning by the structural designer: "What are the loads for this member? What are the conditions which govern design of this area of the fuselage? Etc., Etc." Generally if the needs of the designer are clearly satisfied in the formulated structural criteria, then the basis for understanding between customer and contractor is thereby also assured.

In the near future a new MIL spec series containing structural criteria for aircraft is to be issued (1),<sup>1</sup> superseding the current Air Force spec series (2) and the current Navy specification (3). The new series will contain considerable new material particularly in the area of fatigue and thermal environments. Nonetheless, they admittedly do not adequately

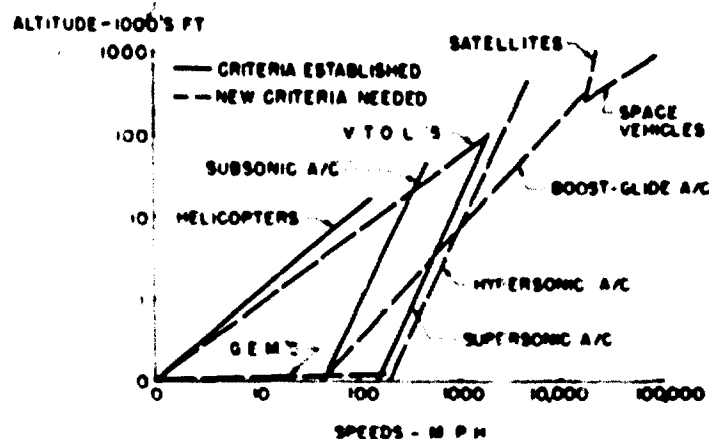


Fig. 1 Family of flight vehicles

ly cover VTOL, boost-glide, satellite, space, and GEM vehicles.

Fig. 1 shows flight-vehicle operating regimes, with solid lines indicating vehicles for which adequate criteria are available, and dashed lines showing those which are inadequately covered. Furthermore, in the field of guided-missile design, the existing structural criteria specification (4) is considered by most structural engineers as being rather limited in usefulness as a designer's tool. Recent Air Force sponsored studies in the missile-criteria field by O. R. Anderson (5) and in the thermal criteria field by Buckley and Strasser of Bell Aircraft (6), point to considerable criteria development work still to be completed. Based on continuing studies at Bell Aircraft in the structural criteria field, this paper presents a broad approach to achieve an orderly formulation of criteria to fill these growing needs.

## PRESENT STRUCTURAL SPECIFICATION COVERAGE

In order to satisfy the two basic needs which are the reasons for their existence, structural criteria specifications must cover several fundamental "requirements" areas. These are indicated in Fig. 2, in which it is shown that three interdependent major areas of criteria are analytical presumptions, design conditions and assumptions, and structural test precedents. As pointed out by the author in an earlier paper (7) the extent of conservatism in one area affects the need for conservatism in the other two. Thus, if structural tests are extensive, then required paper analyses can be minimized. Or if design presumptions are conservative, scope of tests can be reduced. Nonetheless, in order for the designer to proceed with his work scientifically, he must have stipulated for him information falling within the box shown under the "design" block. Also, for the customer to define fully what strength level he actually desires, these same items must be spelled out clearly. In the long run it is not only better for the designer to have these presumptions defined, but also from the contractor's aspect work can proceed more rapidly and with greater assurance of customer satisfaction when this is true.

<sup>1</sup> Numbers in parentheses designate References at the end of the paper.

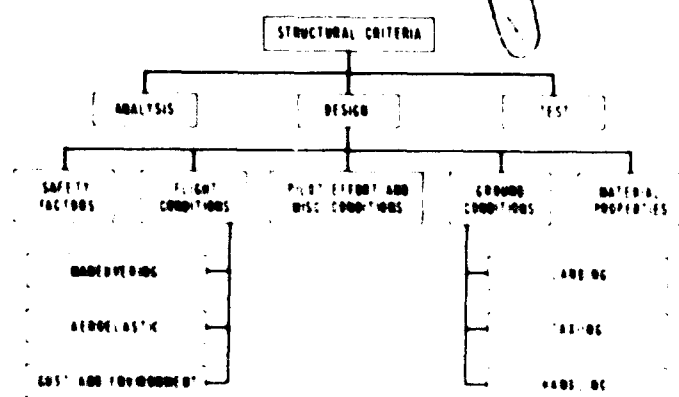


Fig. 2 Basic criteria for aircraft design

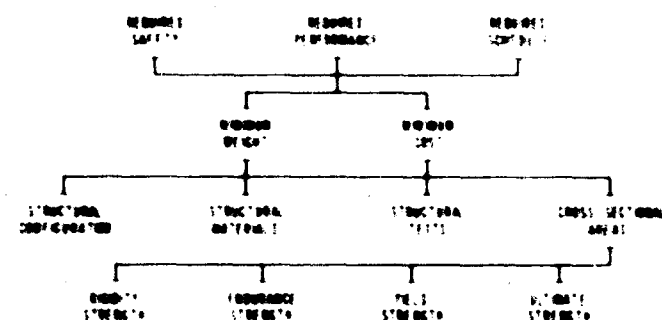


Fig. 3 Elements of good structural design

The current specifications previously mentioned provide these requirements quite adequately for the vehicles for which considerable operational experience now exists. However, owing to the manner in which requirements are assembled, when a new category of flight vehicle evolves it becomes necessary to create a completely new specification -- and accordingly, helicopters and missiles are each covered separately from aircraft.

When past experience in criteria formulation is reviewed, it is found, however, that considerable similarity exists in some areas for a wide variety of vehicles and operating regimes. It is found that for piloted vehicles there has been almost universal acceptance of a 1.5 ultimate factor of safety in one way or another. Also, the "pilot-endurance" and "pilot-effort" load conditions remain essentially intact year after year (that is, the pilot can push, kick, turn, and crank controls with the same force today as he could 30 or 40 years ago). Gust environments are basically unmodified, be it for a Piper Cub or for a B-58. Fundamental fatigue-strength concepts, and structural analysis and test concepts, are broadly speaking similar for most flight vehicles. Material allowable data and presumptions are universally applicable. Land and water load conditions fit into relatively simply definable categories having rather specific ranges of severity depending on several parameters which vary with vehicle type and its service utilization. The "limit-load

concept" is accepted almost universally as the most expedient analytical method for flight-vehicle design (see discussion in reference 7).

As new vehicles are evolved, many of the criteria elements described in the foregoing continue to be applicable and acceptable for use on the advanced concept. Changes, of course, are necessitated at least in some of the condition combinations. To better understand the nature of requirements for new criteria, the structural designers' basic needs are reviewed and analyzed in the following section.

## STRUCTURAL DESIGNERS' NEEDS

The fundamental precept for the structural designer is "Provide adequate strength to assure desired safety and performance, at minimum weight and cost." This is illustrated and expanded somewhat in Fig. 3. The designer proceeds with his work of selection of an efficient structural configuration, utilizing optimum materials with minimum cross-sectional areas -- as dictated by the basic precept depicted by the five topmost blocks. The "structural tests" block was shown because, in addition to the obvious analytical efforts necessary to achieve efficient design, tests become a major tool in assuring that the basic precept is followed.

Of fundamental significance to the designer are the facts depicted by the bottom row of blocks in Fig. 3. While minimum weight is considerably affected by structural configuration and material selection, the final determining factor defining weight is cross-sectional areas. Thus, when configuration is fixed, and material selected, the actual determination of structural weight does not occur until elemental stresses or strains are determined for one of the four strength criteria -- namely, ultimate strength, yield strength, endurance strength, or rigidity strength. Each of these strengths requires safety-factor specification, load and environment-condition specification, and test and analysis presumptions.

For each structural element in every part of the vehicle, one condition in one of the four strength categories finally determines the required cross-sectional area. Very often this particular condition is one which was not specifically defined by the basic structural criteria. Thus, it invariably and frequently becomes necessary for the designer (or detail stress analyst) to improvise a specific "criterion" applicable to a particular structural section. However, the basis for the condition thus formulated must generally be indicated by the conditions provided in the basic criteria. Furthermore, the safety-factor and other general presumptions must be understood adequately so that the specific condition thus created is truly compatible with the over-all design philosophy.

Too often the basic criteria and the resulting load and deflection analyses have become primarily an exercise for the sophisticated load specialist. In far too many cases it has become quite evident that the designer is expected somehow to provide structural configuration and element cross-sectional areas so that the analyst can accurately proceed with his analytical predictions! In such cases it often is true

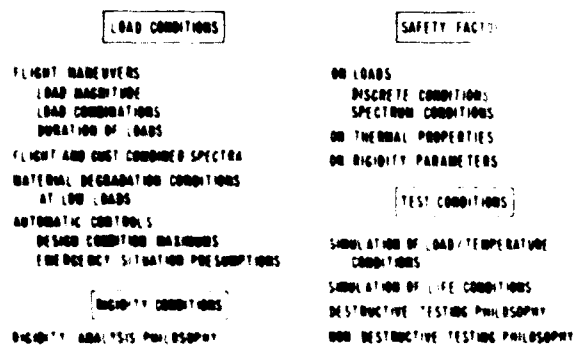


Fig. 4. Supersonic/hypersonic aircraft basic criteria needs.

TABLE 1. FUTURE VEHICLE LOAD CRITERIA NEEDS

LOAD CONDITION	VEHICLE TYPE				
	SUPERSONIC & HYPERSONIC	BOOST GLIDE	SATELLITE AND SPACE	HYPERSONIC	CEM
MANEUVER TEMPERATURE SPECTRA	P	P	S	P	
MANEUVER AND GUST SPECTRA	P	P	S	P	
MATERIAL DEGRADATION	P	P	P	P	
NEW ENVIRONMENTS	S	P	P	S	
BOOST AND RE-ENTRY		P	P		
LOAD DISTRIBUTIONS	P	S	S	P	S
NEW LOADING CRITERIA	S	S	S	P	P
AUTOMATIC CONTROLS	S	P	P	S	S
TAXI AND GROUND HANDLING	S	P	P	S	P
EMERGENCY SITUATIONS	S	P	P	P	P
SPECIAL OPERATION LOADS		S	P	P	P

P-PRIMARY DESIGN CONDITIONS S-SECONDARY DESIGN CONDITIONS

that the formal criteria become so involved that in fact the actual design selection was based on an unofficial, under-the-table, simplified criterion which the designer utilized in calculating stresses and strains to come up with structural cross-sectional areas. Very often in these cases the final "accurate," load-and-stress analysis is not completed until after the airplane has been flown for several months or even years!

The importance of providing usable, easily understood criteria cannot be overstated. In the author's experience it has been evident, more often than not, that when structural design conditions cannot be conveyed quickly and understandably to the designer for his use, the assumptions necessary to accomplish the more complex analysis seriously jeopardize the reliability of results. In such cases acceptance of conservative, simplifying assumptions -- at least in the initial design stress and/or deflection analysis -- expedites reliable accomplishment of design and usually with very little (if any) penalty in weight. It is contended, therefore, that a primary objective of the basic structural criteria should be to provide criteria which, with minimum preparatory analysis, are readily understandable to (and usable by) the designer. If this link is not provided, irretrievable weight penalties are believed to occur, and appreciably in excess of those introduced because of the less sophisticated analyses.

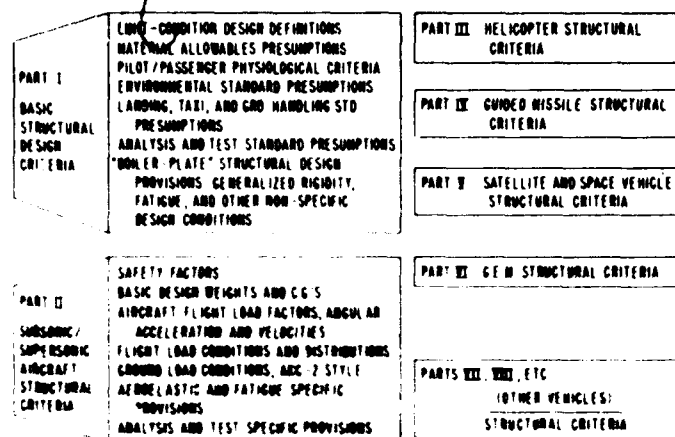


Fig. 5. Work for a general structural criteria specification.

## NEW CRITERIA SITUATIONS

Among the advanced vehicle types which require formulation of new structural criteria, the vehicles broadly classified as "hypersonic aircraft" (such as the Bell X-2 and the North American X-15 and B-70) have received the most attention. As discussed by the author in references (7) and (8), "temperature" and "time" are two new parameters requiring definition for design purposes, ranking in importance with "load" and "safety-factor" considerations. And, unlike the situation which has existed with "fatigue," where designs were often completed without any analytical treatment of fatigue, the structural designer cannot proceed with his design work at all until some thermal and time criteria are stipulated. Many studies have been performed to provide analytical tools and criteria concepts for these ultra-high-speed aircraft, such as reference (6) and (9) sponsored by the Air Force and performed by Bell Aircraft. But in spite of all that has been done, little crystallization into suitable specification requirements has as yet been accomplished. Fig. 4 provides a brief summary of kinds of criteria which are required. Since the aforementioned references cover this criteria area quite completely, a more extensive restatement of unresolved criteria problems for this type of aircraft need not be included in this paper.

Moving to more advanced vehicle areas, some of the criteria situations for boost-glide aircraft, manned satellite vehicles, and manned space craft will be described. Although, this paper specifically avoids the broad and varied area of missile criteria, the flight situations of these three categories of piloted vehicles will have much similarity with some varieties of guided missiles. The main similarity will be the need to use criteria which place dependence upon preprogrammed automatic maneuvers. In the earlier aircraft types (subsonic, supersonic, and even hypersonic) the control inputs to be initiated at different times by the pilot are the primary source of design conditions, with automatic controls providing a rather minor category of emergency or secondary design conditions. In the more advanced vehicle

types, exactly the reverse situation is already evident: that is, automatic controlled flight conditions provide the primary source of structural criteria, with emergency manually controlled conditions being considered secondary and often, by design in the interests of weight savings, made to be no more critical than the required automatic flight conditions. Also for these advanced vehicle types, there often will be one or more pilotless boost stages which must be looked upon as a cross between a missile and a manned vehicle. There will be "launch," "boost," "boost-separation," and "re-entry" phases, in many respects quite related to the flight phases considered in structural design of ICBM and IRBM vehicles. In addition, there must also be determined new criteria for relatively strange glide-landing, and other novel vehicle recovery schemes. Scattered throughout the flight plan there will be a variety of new condition situations resulting from several types of radiation exposure, meteoric-dust onslaughts, and potentially severe thermal-exposure variations.

Falling back to more down-to-earth type vehicles, there is increasing interest in "vertical-take-off and landing" (VTOL) aircraft. As shown in Fig. 1, these aircraft may vary in speed capability from hovering, zero forward speed, to speeds equal to that of contemporary supersonic aircraft, and perhaps eventually, to that of hypersonic aircraft. At present, VTOL is accomplished by development of more than 1 G of lift force primarily by use of deflected jet exhaust, deflected propeller flow, and by rotating or fixed ducted fans. For these aircraft, there are several new categories of flight conditions resulting in some cases from in-flight rotations of major components of the aircraft, and in all cases from the need to consider "transition flight" situations. The purely vertical-descent landing characteristic provides the need to create landing design criteria which embody some of the features of both helicopter and conventional aircraft criteria.

A somewhat unexpected breed of vehicles has been occupying the attentions of more and more criteria engineers: namely, the "ground effect machine" (GEM). Some people argue that these are land or water vehicles rather than flight vehicles. But this question is immaterial to the structural designer, because it is unquestionably true that light weight is important for these machines, and hence the use of the "limit-condition" design philosophy is obviously logical. In studying the operating situations encountered, however, similarity with aircraft is almost nonexistent. For these vehicles, most of the structural design conditions during operation stem from contact with the ground or water. These loads vary from 1 G "resting" loads, with the vehicle supported at a single point amidship or at two points at the bow and at the stern, to high G dynamic loads resulting from dropping from cruising height above the surface or from striking waves or obstructions while in forward or sidewise motion. Much remains to be experienced, and learned, before generally accepted structural design criteria are crystallized.

A summary of the kinds of new load criteria needed for the various vehicles discussed in the foregoing is provided in Table 1.

## CONCLUSIONS

The most striking aspect of a review such as this of the entire realm of flight-vehicle configurations is not so much the dissimilarities of the conditions encountered, but rather the similarity of basic approach which the aircraft structural criteria engineer is able to flexibly adopt. It is obviously logical to apply the limit-condition criteria approach in every case. It also is sensible to utilize similar analytical and test presumptions, and obviously the same basic material-allowables data previously used are still completely applicable -- with some new categories of physical characteristics merely added. Primarily, there are new load conditions, and also new structural life provisions, to be created. The basic framework remains fundamentally unchanged.

Accordingly, the author advocates viewing flight-vehicle structural criteria from a much broader standpoint than heretofore. Many of the structural criteria requirements contained in our aircraft (1, 2, 3), helicopter (10), and missile (4) specifications are entirely repetitive. Likewise, this same category of criteria is readily applicable to the vehicles discussed herein for which no applicable general specifications exist today. This, incidentally, is equally true in the cases of both civil as well as military flight vehicles. It therefore is considered both logical and practical to reflect these facts in some future rearrangement of structural criteria specifications, such as that shown in Fig. 5. Here it is suggested that the sizable amount of common criteria presumptions be contained in a single specification, or a single part of one all-embracing spec. The subsequent parts would then only contain such available specific criteria which can be defined for a specific flight-vehicle type. It is easily conceivable that there might be seven or eight subsequent parts, covering that many different vehicle types.

As the flight-vehicle science has rapidly progressed, the structural designer has constantly been forced to "start from scratch." The author on several occasions has found himself starting off the structural section of a flight-vehicle model specification by writing: "The structural design requirements of MIL-\_\_\_\_\_ are not applicable." Especially for the designer, who is usually anxious to evolve the lines and details on his drawings from best available, time-proven, knowledge, such a beginning is not very reassuring. It would be far better to start with: "The Part I basic structural design criteria for MIL-\_\_\_\_\_ is applicable. The specific design load conditions specified in Part V, sections \_\_\_\_, \_\_\_\_, and \_\_\_\_ are applicable. Supplementary design conditions necessitated by the specific operating characteristics of this vehicle shall be as specified below."

As described herein, the field of structural criteria is expanding rapidly. Much of its essential philosophy and characteristics do, however, continue to remain unchanged. The structural designer who learns to appreciate and utilize this fact, advances himself a long way forward to achieving the solutions of structural criteria problems for new and untested flight -- vehicle configurations.

Finally, this approach to formulation of structural criterion

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